THE AUTOSTEREOGRAM

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Abstract

A new technique for the presentation of cyclopean stereograms is described, in which complete information for the two eyes is contained in a single, printed image. Such "autostereograms" may be generated to contain an unlimited range of 3-D depth forms within certain constraints. The depth image also occurs at multiple depth planes in front of and behind the physical plane, and may be designed to progress recursively through these multiple planes. Specific autostereograms may be generated so as to be used to continuously tile an indefinitely large surface. Further types can be devised to produce different depth images in the two orthogonal viewing orientations. Finally, the autostereogram principle is used to explore cyclopean perception based on the percept of binocular luster, which has surprising properties.

Within the first decade of the discovery of stereoscopic vision by Wheatstone (1838), numerous methods of presentation of stereograms had been developed. These include Wheatstone's mirror stereoscope, the lens stereoscope and various prismatic stereoscopes (Brewster, 1851). Later developments allowed the separate images destined for the two eyes to be optically superimposed, including the color separation method and the cross-polarization method. Only one approach, the lenticular screen method used in 3-D picture postcards and various advertising applications, provides a degree of stereopsis without recourse to some kind of viewing apparatus. Even the lenticular screen method requires elaborate reproduction techniques and cannot be used in conventionally printed material.

This paper describes a new stereoscopic technique that allows the stereoscopic presentation of almost any three dimensional form from a single printed image requiring no viewing apparatus. It has the additional feature of being in Julesz' (1960) random-dot format of stereogram, in which the 3-D form bypasses the monocular processes and is visible only which stereoscopic fusion is obtained. The technique does require a minimum of oculomotor skill on the part of the observer, but once developed in an initial viewing session of 5 - 10 minutes, rapid perception of all kinds of stereoscopic images is readily achieved by most observers.

The principle of the autostereogram

Any horizontally repeating pattern, such as wallpaper, may be viewed with the eyes converged (or diverged, if the repetition angle is sufficiently small) so that a given repetition cycle in one eye is in correspondence with the adjacent repetition cycle in the other eye. The effect is to produce a stereoscopic plane at the new convergence point, in front of (or behind) the physical plant of the pattern, and is known as the "wallpaper effect" (Brewster, 1844). If the pattern is designed so that there are small horizontal deviations in each cycle of the repetition relative to the adjacent cycles, Brewster also noted that these will produce disparate regions relative to the perceived stereoscopic plane, which will be perceived at different stereoscopic depths. By suitable manipulations of the relative deviations almost any stereoscopic figure can be generated.

A previous application of this principle was demonstrated by Burt and Julesz (1980), where they used repeating line images with small shifts in line orientation to display line segments tilted in depth. Combination of this principle with that of random-dot stereograms (Julesz, 1960) allows the elimination of monocular cues to the depth image. The base pattern is then a repetitive random dot array (Julesz, 1971; Tyler and Chang, 1977), which has the property that there is noparticular point at which the repetition cycle may be said to begin; the repetition is continuous

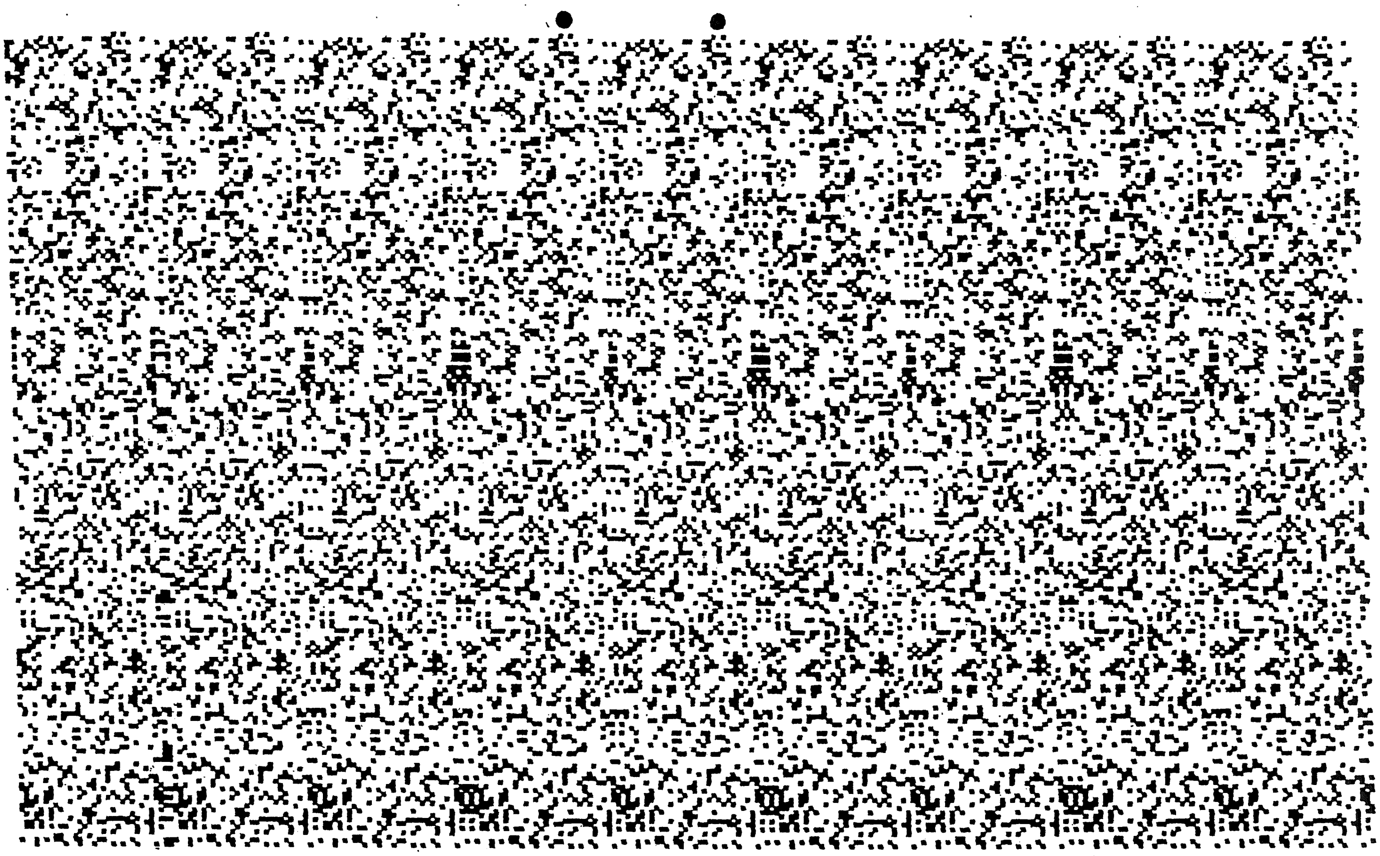


Figure 1. Autostereogram of a checkerboard in depth. Cross the eyes slightly so that the two solid fixation dots appear as three dots in a line. Focus on the center one until depth is perceived in the rest of the display.

and is defined only by a repetition width. The repetition width corresponds to the vergence angle required to view the figure in the stereoscopic mode, and is inherently much smaller than the total width of the figure. As a result, there is no limit of the size of autostereogram that can be viewed, since the vergence angle is determined by the repetition width rather than the overall size.

A simple autostereogram of this type is shown in Fig. 1, depicting a checkerboard in which the square size is commensurate with the repetition width of 20 dots. This is achieved by alternately omitting and including an extra (randomly selected) dot every 20th position in each horizontal line. The alternation is itself alternated vertically every 20th line to produce the effect of a checkerboard in the vertical direction.

To view the autostereogram, the simplest method is to hold up a finger in front of the figure about halfway from the face to the page. Look directly at the finger, not at the page. At this distance the two fixation stars near the center of the figure should appear as three stars, the central one binocular and the outer two monocular and subject to interocular suppression. If three stars are not visible, move the finger slowly back and forth until a fixation lock is obtained on the central of the three stars. The convergence distance is now appropriate for viewing the stereoscopic image.

Once the fixation lock is obtained, continue to fixate the central, binocular star steadily until a stereoscopic image appears in the remainder of the field. For some observers it may pop out immediately, while others may have to continue fixating for several minutes before the depth emerges for the first time. In neophytes the depth impression is so unusual that it may be automatically rejected at first by an involuntary refixation, so that repeated attempts may be necessary. However, once it is obtained the stereoscopic impression becomes easier to hold and to regain. When stereopsis is firmly established, the finger may be withdrawn and the gaze moved freely around in the 3-D image for optimal viewing.

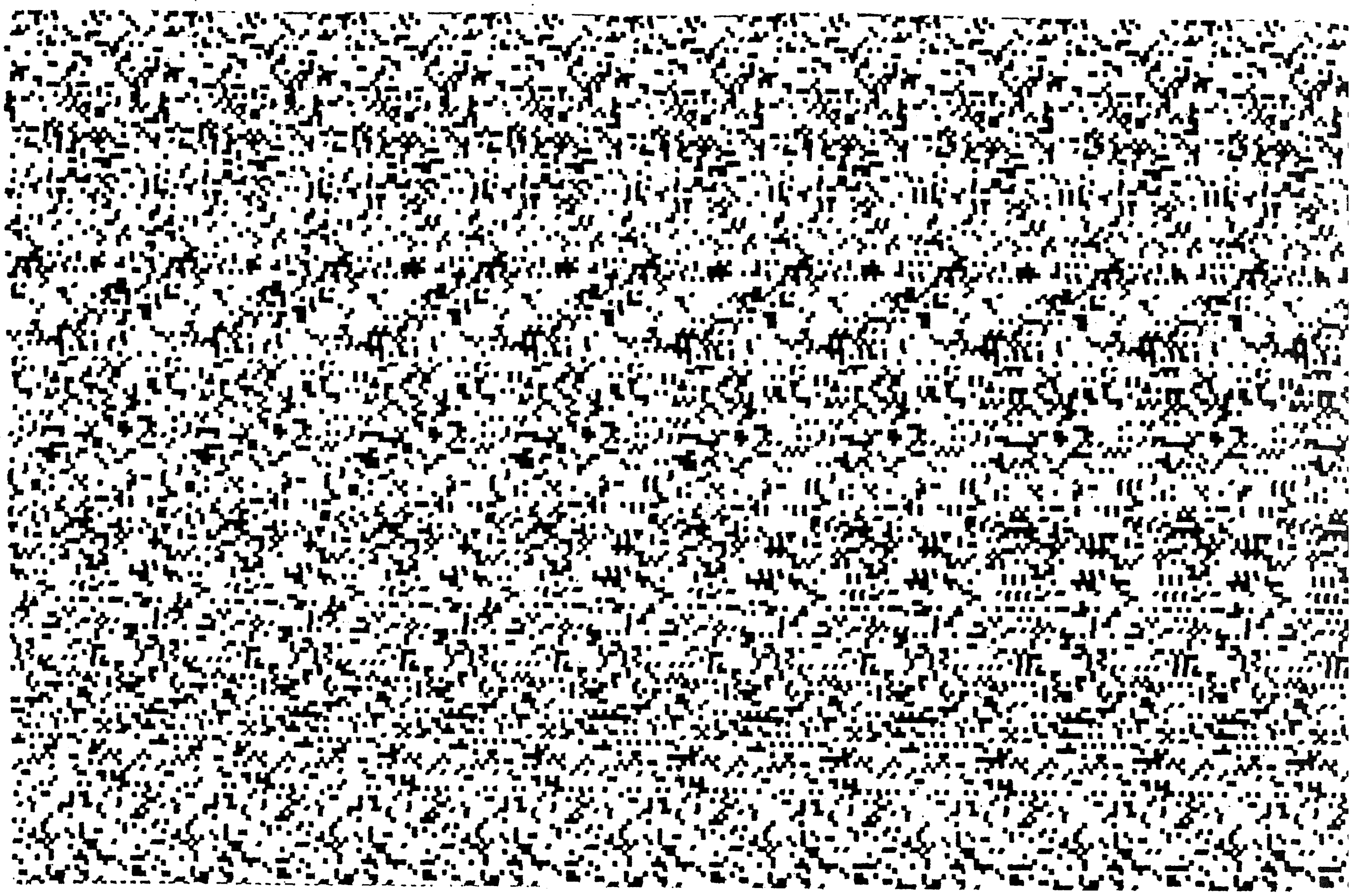


Figure 2. Autostereogram image containing oblique lines independent of the repetition cycle of the random dots.

<u>Autostereogram generation</u>

The autostereogram is based on a series of random dots repeated at a nominal rate that is modulated by the pattern depth. For each horizontal line a number of random dots is generated and stored at the beginning of an array. This number equals the repetition rate plus the greatest pattern depth. The pattern is evaluated for each position on the line and the result of the evaluation added to the repetition rate. The value at the current position in the array minus this number is then plotted and added to the array. For example, to generate a simple checkerboard pattern with a total length of 280 dots, a repetition rate of 30, and each square above or below the plane by a disparity of 2 dots, an array of 320 would be dimensioned. Forty random dots would be generated. To give a depth impression in the zero plane dot 1 would be repeated in array position 31 (a 30 dot shift), 2 in 32, etc., to the end of the plane. At the point when a checkerboard square in front is required, the position 30 - 2 = 28 dots previous would be repeated (e.g. dot 83 to position 111, 84 to 112, etc.) for as long as this square lasts. For the squares behind the zero plane the position 32 dots previous would be repeated.

The repetition rate is determined by two factors. The stereo effect is easier to obtain with a rather small disparity. However, the base rate must be greater than the greatest disparity of the pattern, preferably several times the greatest disparity. The reason is that for a field of depth (D), one less than the repetition rate (RR), only the last dot would be repeated for the whole field (RR+D = 1 where RR = 30, D = -29). In this case A(N) = A(N-1), and the pattern would collapse to either all white or all black dots.

As the pattern disparity changes some dots are lost at the repeat interval. With few, small pattern changes (such as checkerboard with minimal depth) this loss is acceptable, even unnoticeable. In cases where depth changes approach the repetition size , deterioration of the randomness is apparent in non-stereo, at each shift in depth from the previous position.

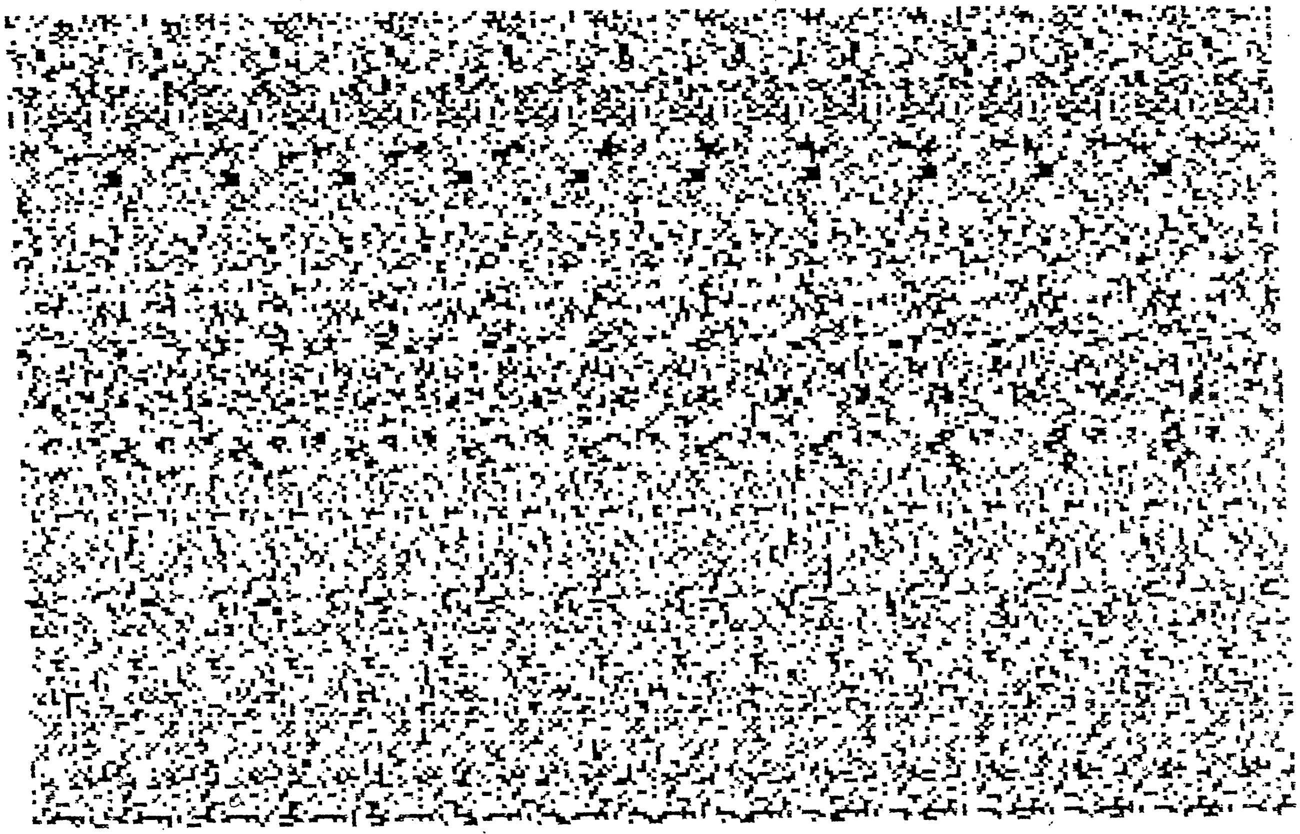


Figure 3. Autostereogram image of a horizontal stereograting with a sinusoidal profile in depth, giving the impression of a series of corrugated furrows.

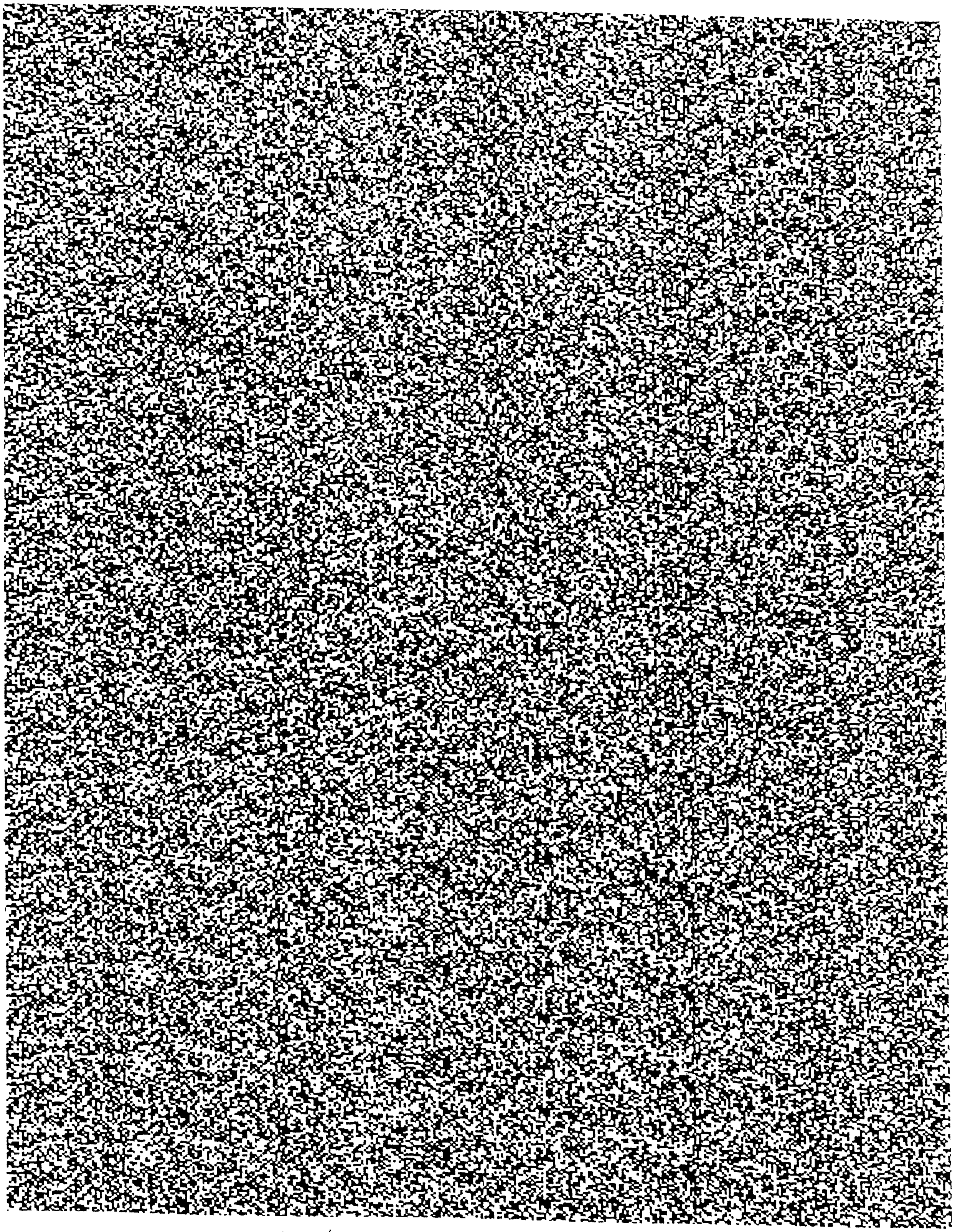
An interesting precursor of the autostereogram principle was demonstrated by Julesz and Johnson (1966). Their aim was to generate ambiguous random-dot stereograms containing two distinct surfaces in depth, which were to be viewed in standard polaroid or anaglyph format. The generation algorithm was complex and required point by point specification of each dot to conform to a position on each of the separate, superimposed surfaces. If one surface was flat and corresponded to the plane of the page, this algorithm has the effect of producing the same kind of array as our repetition width algorithm. Thus, unremarked by Julesz and Johnson, one of their monocular images can be viewed in depth by the autostereogram procedure. It also exhibits other features of autostereograms discussed below.

Complex autostereograms

It should be clear that the key to producing a given disparity at some point in the image is to set the repetition width of the random-dot sequence to the appropriate value at that point. A shorter repetition width produces a crossed disparity relative to the mean repetition width, while a longer one produces an uncrossed disparity. To change the disparity at any point, only the repetition width needs to be altered at that point. The only limitation on the amount and position of the disparities produced is the size of the random-dot elements.

Thus, for example, a stereoscopic edge of any orientation may be produced by a step change in the repetition width along any (imaginary) line in the autostereogram. An example using oblique lines is shown in Fig. 2, with apologies to Roy Lichtenstein, the pop artist.

A further freedom of the repetition width principle is that the depth may change as rapidly as the dot size allows, in either the horizontal or vertical direction. This essentially allows any three-dimensional form to be represented, although smooth surfaces are quantized into disparity levels determined by the discrete dot size used for the images. An example is given in Fig. 3, showing a sinusoidal depth profile of high frequency bars with a horizontal orientation.



... inspired by Leonardo, giving an extended field of view

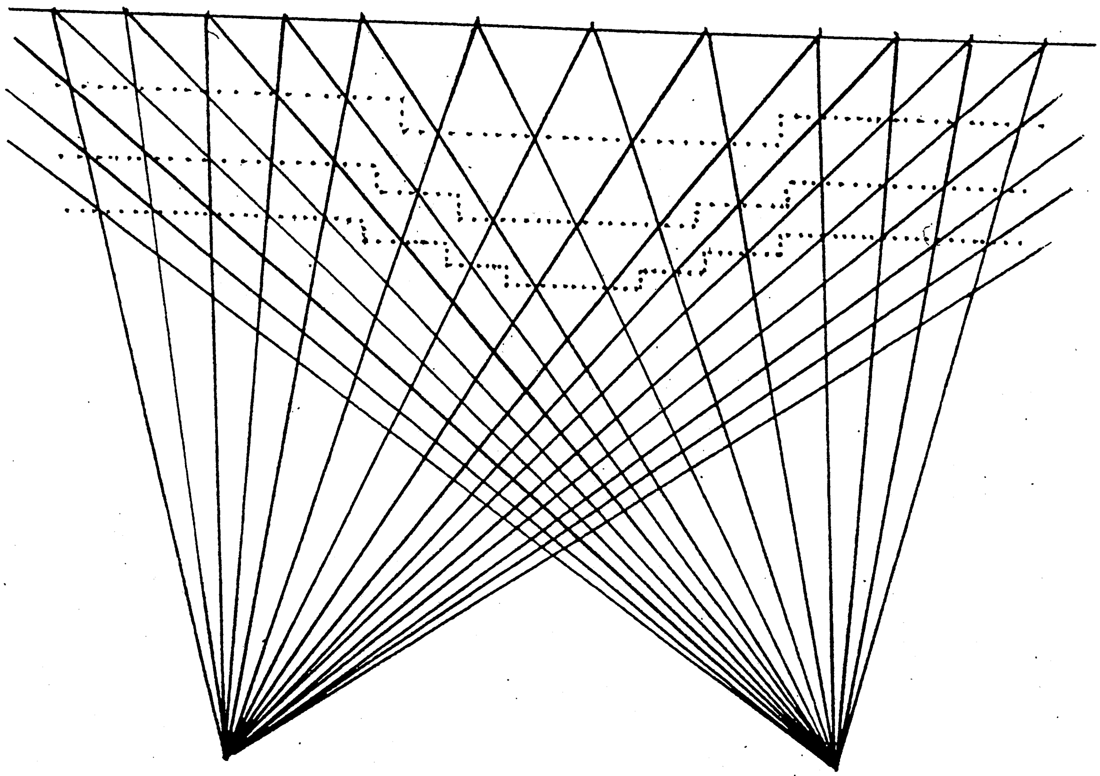


Figure 5. Illustration of the multiple depth planes present in an autostereogram. Different planes with differnt depths images (dotted lines) may be viewed by appropriate convergence.

Parenthetically, it may be noted that the sinusoidal stereograting image of the type shown in Fig. 3 was developed to explore the stereoscopic system (Tyler, 1974) in much the same way that sinusoidal contrast gratings have been used to study the contour processing system. Many of the curious results of probing the stereoscopic system with stereogratings have been reviewed in Tyler (1983). These show, for example, that in addition to a cyclopean level of depth processing, there is a hypercyclopean level in the brain analyzing the form of the cyclopean depth images. The hypercyclopean level seems to contain processes selective for both orientation and spatial frequency within the stereoscopic depth image.

Since both horizontal and vertical depth surfaces can be generated, even more complex images are possible. Figure 4 is a vortex image inspired by Leonardo da Vinci's interest in rotating vortices in his notebooks from the Windsor Castle collection. As with all complex random-dot stereograms, it may take longer for the perceived depth to reach fruition in these complex images.

The limitation of disparity quantization imposed by the dot size may be overcome with the use of non-binary noise as a basis for the image. All the examples presented here are based on binary (black/white) noise. If the noise were instead generated in multiple grey levels (e.g. eight-bit noise with 256 grey levels), then the repetition width could be shifted in increments of 1/256 of the dot size. Such small shifts can be achieved by defining a high-resolution noise pattern and recomputing the grey levels associated with each incremental position of its repetition cycle as the required disparity changes. For a reasonable dot size of 2' diameter, this technique should take the disparity resolution down to 1", well below the perceptual resolution limit of about 5".

Multiple depth planes

Up to this point we have emphasized the depth image present around the level of one mean repetition width in front of the printed page. It is easy to see that an additional autostereographic image will be produced if convergence occurs across two mean repetition widths, as illustrated in Fig. 5. But just as the first level of convergence contains differential depth information that is not

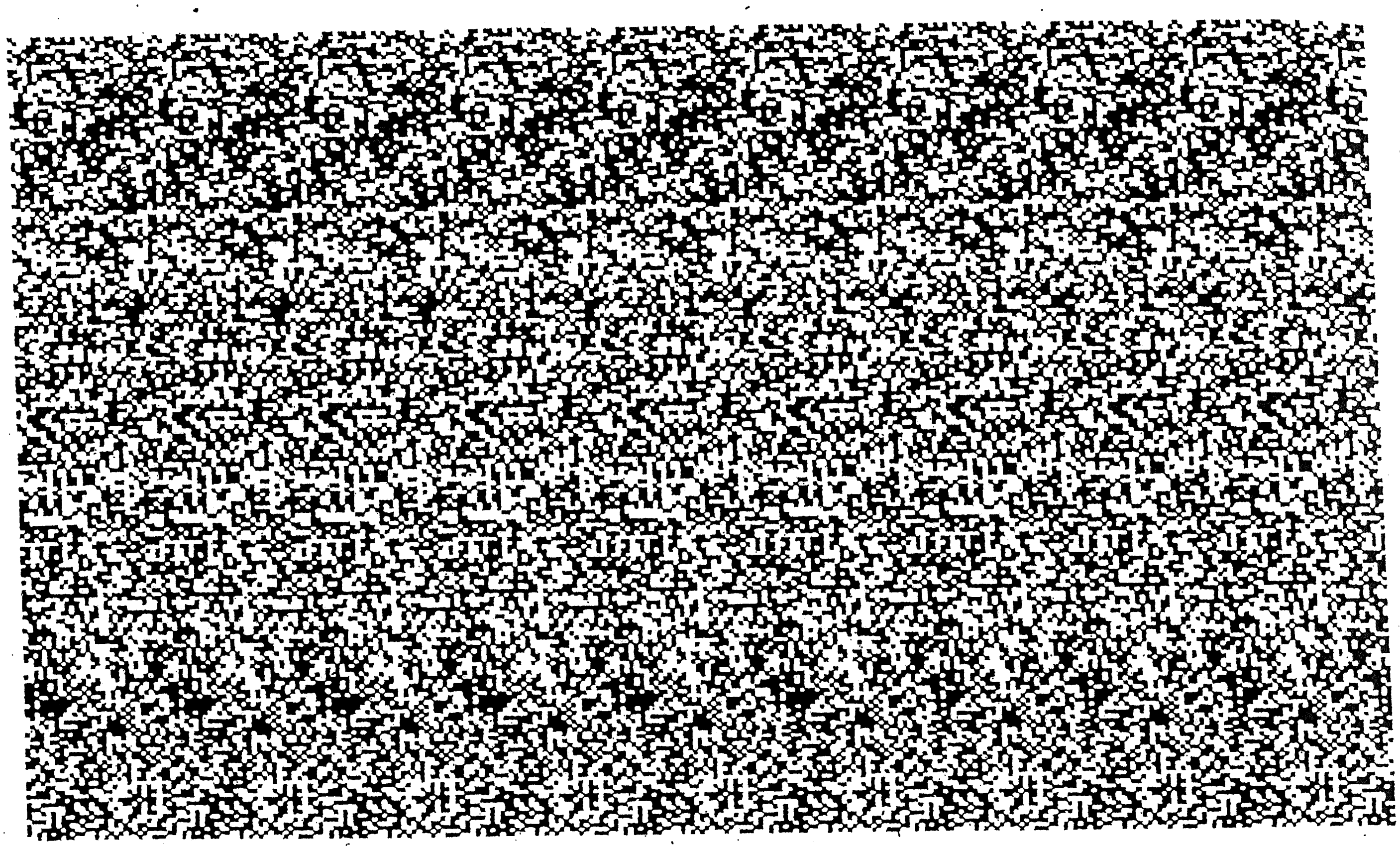


Figure 6. Autostereogram image of a heart, which may be concatenated by viewing at various depth levels.

present in the flat image in the plane of the page, so the second convergence level contains twice the differential disparity of the first. It also involves a relative shift of an extra cycle, so that the result is as if two of the computed disparity images were added together, with an extra one cycle shift of the mean repetition width.

This feature of the autostereogram may be illustrated with the image of a heart generated as a Valentine's Day card (Fig. 6). The first level of convergence, with fusion to produce three fixation stars as described above, reveals a simple heart in depth. The second level, obtained by moving the finger closer to the face as to produce four equally spaced fixation starts (now all monocular), gives two overlapping hearts with extra depth at their intersection. With even greater convergence, three or even four levels of hearts in a stack may be perceived.

Similar multiple depth profiles may be seen in the previous autostereograms. However, the checkerboard image of Fig. 1 is not so successful, since the check size is equal to the repetition width, so that the second level of convergence produces cancellation between the checks and results in a flat plane.

A further range of depth images exist behind the plane of the page. For many observers these are more difficult to reach, since one cannot view a finger behind the page. There are two techniques to perceive these uncrossed depth planes. One is to allow the eyes to diverge until three fixation stars are visible in uncrossed disparity, and then fixate the central (binocular) one until depth appears. The other is to look at a distant object behind and just above the autostereogram, and then bring the gaze down to the image without changing the vergence angle. With practice, one can then lock on to one or two of the uncrossed depth images. Once obtained, it will be seen that the depth is reversed, so that what was a crossed disparity in the forward depth images becomes an uncrossed disparity in the rear depth images. The raised heart of Fig. 6 becomes a heart-shaped slot, the vortex of Fig. 4 is seen from the inside, and so on.

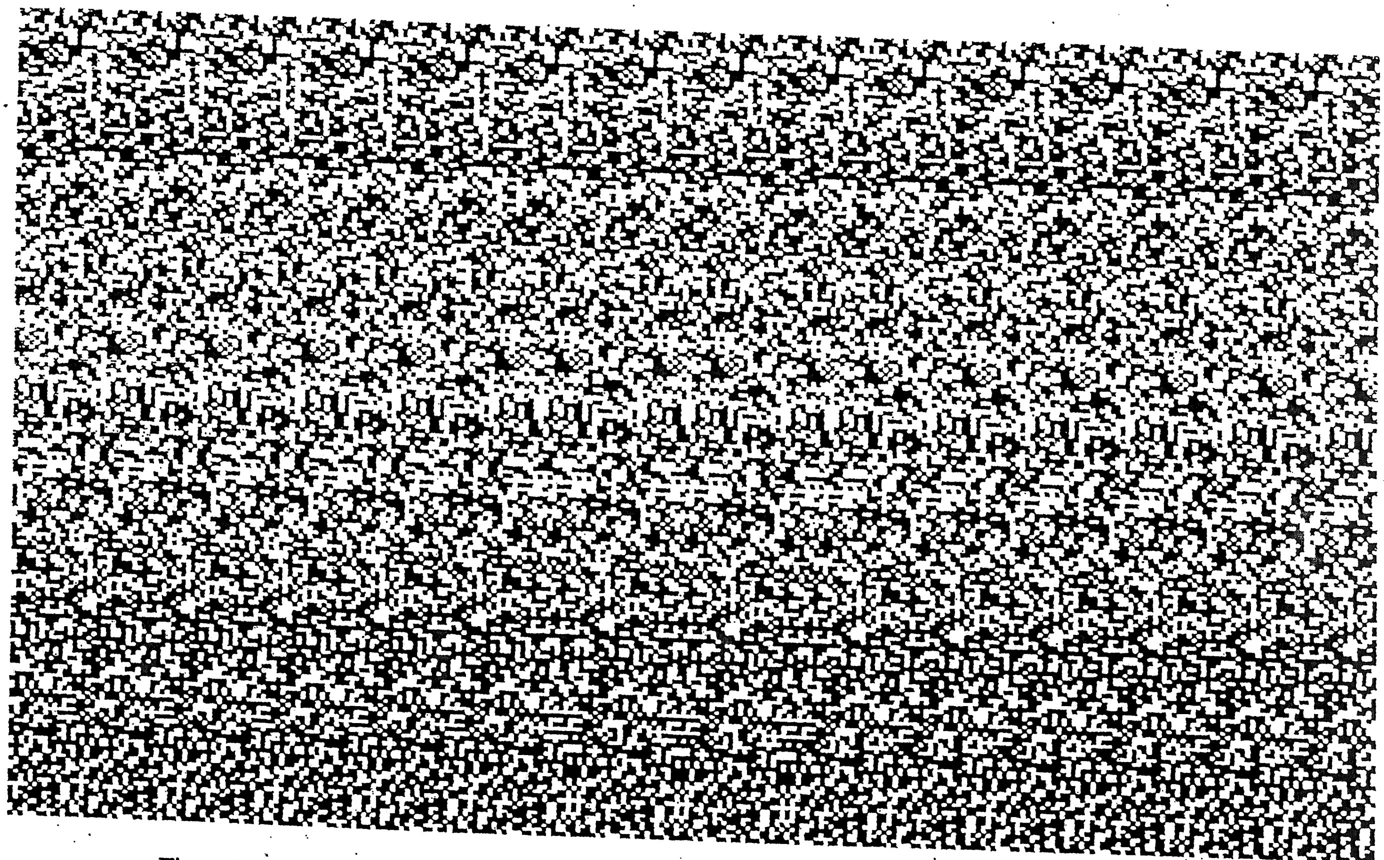


Figure 7. Autostereogram image of a staircase, which may be ascended recursively by maintaining convergence from the top of one flight of steps as the eyes are shifted to the bottom of the next.

Recursive autostereograms

Given the presence of multiple depth planes in autostereograms, it is appealing to ask whether it is possible to arrange the depth planes so that convergence can move progressively from one plane to the next, so that the image is continuous through the third dimension, rather than being present in a series of discrete planes as depicted in Fig. 6. One may envisage a series of steps ascending towards the face, up which fixation can travel in an endless sequence reminiscent of an engraving by M.C. Escher.

Two versions of such a staircase are shown in Figs. 7 & 8, using a mean repetition width of 20 and depths from 10 to 30 repetition widths. When fixation reaches the point where the repetition width is 30, it corresponds to a width of 10 at the second level (mean width of 40). Hence the staircase continues to climb around on itself in a recursive fashion. The stereoimage becomes more complex as higher levels are reached.

There are limitations on recursion in autostereograms. The total range of depth is determined by the limits of convergence (or divergence) of the eyes, so the recursion cannot go on indefinitely. Also, there is a lower limit to how close the first step can approach the plane of the page, since at very small repetition widths the pattern becomes ambiguous. With dots large enough to be readily visible, a minimum of about 10 seems to be the smallest practicable width.

A different type of recursive stereogram has been developed by Kontsevich (1986). While not an autostereogram in the simple sense of being a single image, it does employ the repetitive principle to make a depth profile which marches indefinitely upward in disparity as fixation travels around a set of disparity steps. The stereogram is constructed of a simple repetitive pattern seen in one eye and a square annulus containing the disparity step information in the other eye. When fused, the remaining regions inside and outside the annulus are seen as in binocular rivalry between the white page and the random-dot noise. Within the annular region, the eyes can converge on each step in turn and progress up or down the steps as far as the limits on ocular vergence will allow. It is thus the closest to an infinitely ascendable staircase that has been reported.

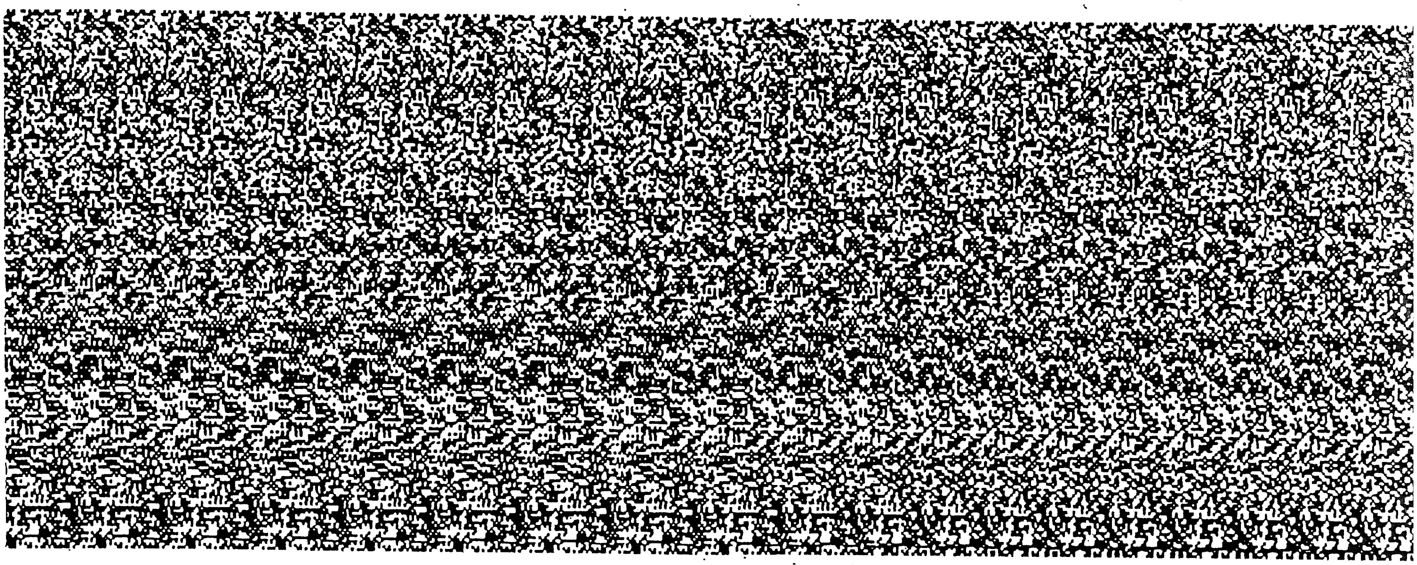


Figure 8. Autostereogram image of two staircases with landings between them. The staircase may be ascended recursively to many stereoscopic levels.

Continuous autostereograms

All the foregoing examples have been isolated depth images. In principle it should be possible to duplicate such images and tile a large surface with them, to produce a type of 3-D wallpaper. In practice, we have found no general algorithm which will allow this to be achieved with an arbitrary stereoimage. There are, however, several approaches which allow the connection of specific types of autostereogram in a repeated fashion.

The problem is not in the vertical direction. Any stereogram can be duplicated and placed above or below itself with no break in the depth impression, because the binocular disparity involves only a horizontal organization of the dot sequence. Each horizontal line is independent of all the others, although of course the depth image can be specified to run smoothly or discontinuously in the vertical direction.

It is the horizontal contiguity which causes a hiatus in the depth impression. In order to make a smooth transition from, say, the right hand edge of one image to the left hand edge of the next, it is necessary for the random-dot pattern to be identical except for the disparity shifts in the strips down both edges. If some arbitrary depth image is generated in the space between the left and right hand edge strips, this will involve the removal and replacement of certain sequences of dots as computation proceeds from left to right. Even if the depth returns at the end to its original value at the beginning, it cannot be generated in such a way that the initial dot sequence is replicated in the final repetition cycle. Thus lateral duplication of the autostereograms described so far will produce a strip of rivalrous or lustrous appearance with unspecified depth between the two stereoimages between the two eyes.

Although there seems to be no general solution to the tiling problem, there are specific solutions which produce quite an extensive range of possible depth images. One approach is to use position in the stored initial sequence as a marker for the removal or insertion of dots as the repetition width is modified so that the depth values return at the end of each line to the starting value. Then the adjacent strips at the edges will match, and a smooth stereoplane will again be obtained.

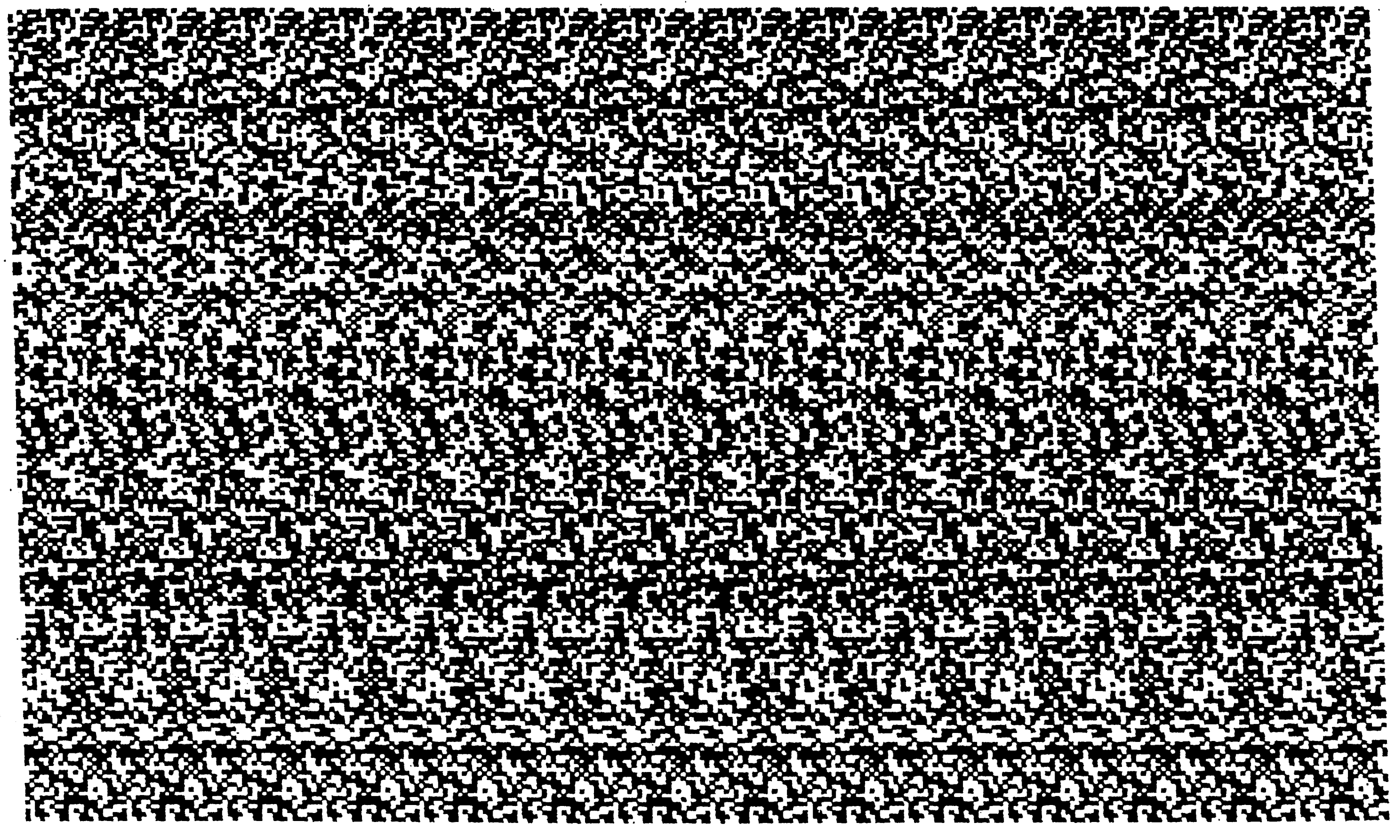


Figure 9. Autostereogram image of fish which may be continuously duplicated in both directions to tile the plane.

In detail, there are four relevant conditions which should be considered. If the repetition width is increased initially to produce crossed depth (in front relative to the crossed convergence point), extra random dots must be added to each cycle. No constraint is required at this stage. As the depth is reduced to return to its initial value, only the extra dots may be removed. The set corresponding to the initial cycle must remain in the image. Thus the depth can only be changed at the discrete points in the image corresponding to the position of the added dots. These points are to be determined by choosing the position closest to that required by the stereoscopic form. The result will be a depth image quantized spatially with respect to the horizontal positions of depth change, although the pattern of quantization may not be.

The other two conditions occur when the repetition width is first decreased to produce uncrossed depth behind fixation. Here the dots must be removed from the image but retained in memory. When the depth is then decreased again to return to the initial depth value, the same dots must be recalled and replaced in the same position in the sequence from which they were removed, again introducing the horizontal quantization constraint.

It is possible to devise sophisticated algorithms to minimize the quantization problem, although it cannot be entirely eliminated. Our approach is to remove or reinsert the new dots only once in each position of the repetition cycle. If a given position has been used for removal, a dot is removed from the nearest unused position on either side. The same is true (independently) for insertions adjacent to each position. This procedure drastically reduces the quantization so that in many cases it is not noticeable.

A second approach to the tiling problem is to generate complementary stereopatterns in the sense that the stereo-image is presented successively in crossed and uncrossed disparities along each line. The complementary patterns must be placed at a horizontal separation corresponding to a complete number of repetition cycles. This arrangement permits an algorithm in which each extra dot that is added to increase the disparity as required in the first image will be removed from the same point in the cycle of the second, complementary disparity image. Conversely, each dot that is removed to form the disparity cycle in the first image may be stored, and then subsequently returned to its position when the negative value of that disparity appears at the same point in the cycle for the complementary presentation of the image.

The result of this algorithm is to generate am autostereogram which ends with precisely the same strip of random dots with which it began. This property allows continuous tiling of the plane with any arbitrary disparity image, providing that it is presented in positive and negative disparity forms along every line of the display. Fig. 9 is an example of such a stereogram with fish images.

Orthogonal autostereograms

If any autostereogram is viewed upside down (rotated 180°), the perceived depth image is unaffected except for the rotation, just as is the case for Julesz stereograms. This rotational independence suggests the challenging problem of designing an autostereogram with an image based on the orthogonal disparities, which may additionally be viewed with a 90° or 270° degree rotation (an orthogonal autostereogram). This may be done with the aim either of presenting the same stereoimage in all viewing directions, as an approximation to a real object in relief, or of concealing two separate images in the same random-dot field. In the second type, each is then revealed like a computational version of the McCullough effect by the orientation of the autostereogram.

Our first approach to the orthogonality problem was simply to program the repetition width changes in two directions, limiting them to small disparities, in the hope that the vertical disparity for one direction would be small enough not to disrupt the horizontal disparity cues in the other. Examples of a bidirectional checkerboard (Fig. 10) show that it is hard to perceive the depth clearly with this technique, although it does allow unlimited forms in both directions.

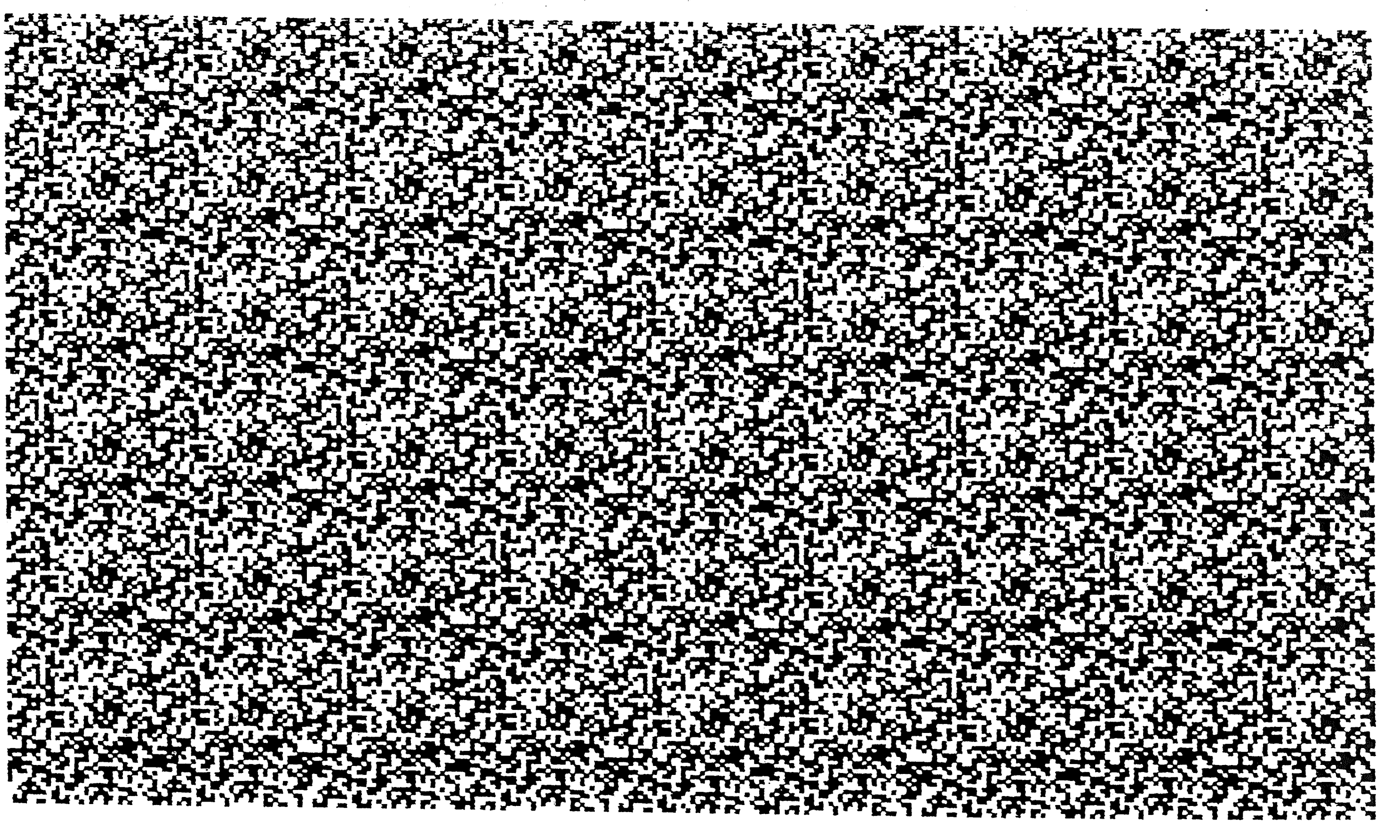


Figure 10. Orthogonal autostereogram image of a checkerboard that may be viewed from all four orientations

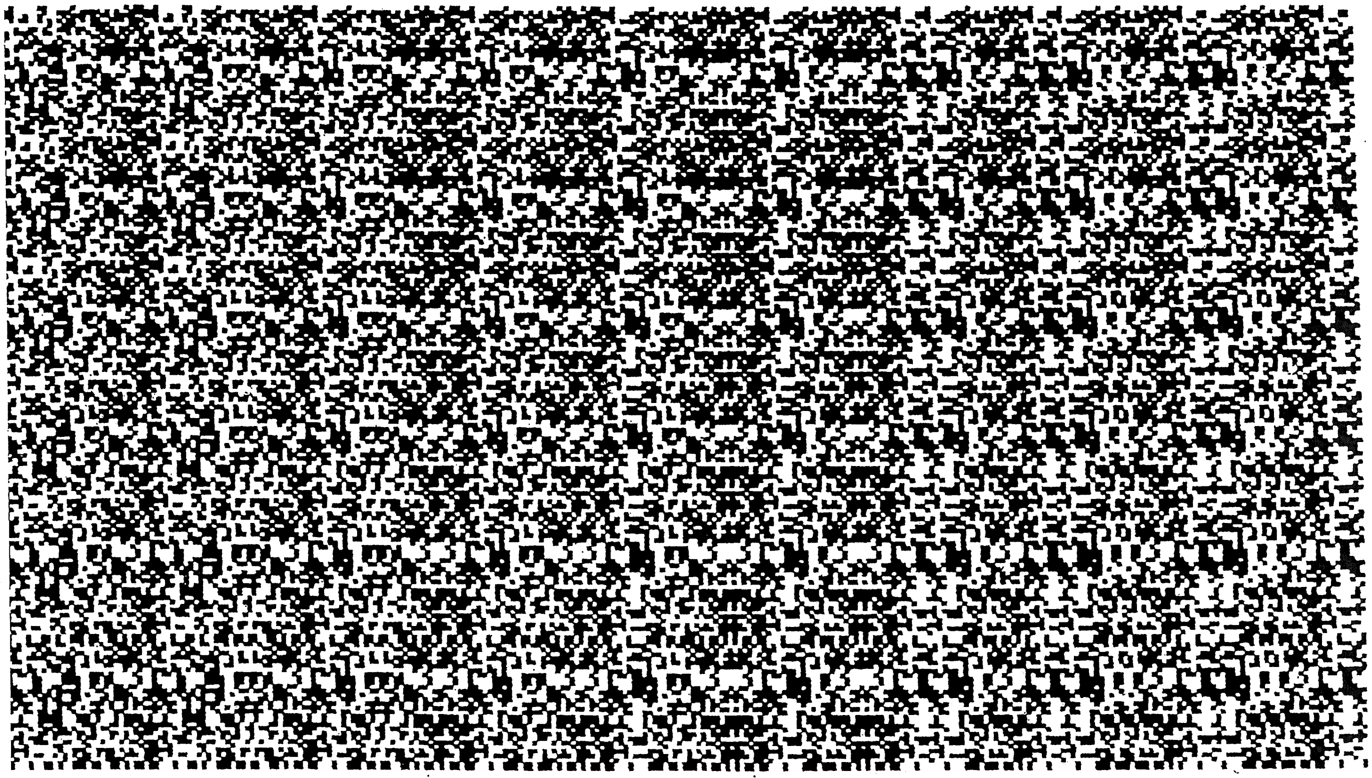


Figure 11. Orthogonal autostereogram image with vertical contour constraints.

A second approach, which was first implemented by Stork and Aberbach (referenced in Stork and Rocca, 1989), is to compute the random-dot image in such a way that the stereoimages for both orientations are perfectly represented in the field. This requires a logically interlocking algorithm, which imposes severe constraints on the type of image that can be generated (as far as we have been able to determine).

One constraint may be described simply. As long as the contours in either image are vertical with respect to their own viewing orientation, they will be horizontal in the other orientation and produce no disruption of those disparities, since each horizontal line in this second orientation is independently specified. An example of this type of "orthodisparate" autostereogram is shown in Fig. 11, with a stepped pyramid in one direction and random vertical bars in the other.

We have not been able to devise a general algorithm for orthogonal autostereograms, but we have found two rather restricted paradigms for extending the image beyond vertical edges. One is limited to horizontal bars and is the same for all four viewing orientations (Fig. 12). A unit square of random dots is set up in sub-elements such that submultiples of the base repetition width occur in horizontal strips in both directions (Fig. 12). Although the large disparities involved here make it difficult to see the depth planes in all three strips simultaneously, the presence of multiple depths in each strip make enjoyable modulations of the depth interlacing if convergence angle is allowed to wander through the depth range. Note that there are vergence levels at which all three planes coincide, forming single flat planes, so a good control over convergence is required for satisfactory viewing of the other possible levels.

The other paradigm also uses the repeated unit concept but constrains the disparity edges to be vertical in one viewing orientation. For this paradigm the unit is the whole of the first vertical strip in this orientation (corresponding to the first horizontal strip in the other viewing orientation). This permits considerable freedom in the second orientation within each unit, allowing a range of disparities to be modulated in either the horizontal or vertical direction, in any combination. When this strip is repeated to complete the image, a substantial range of repeating

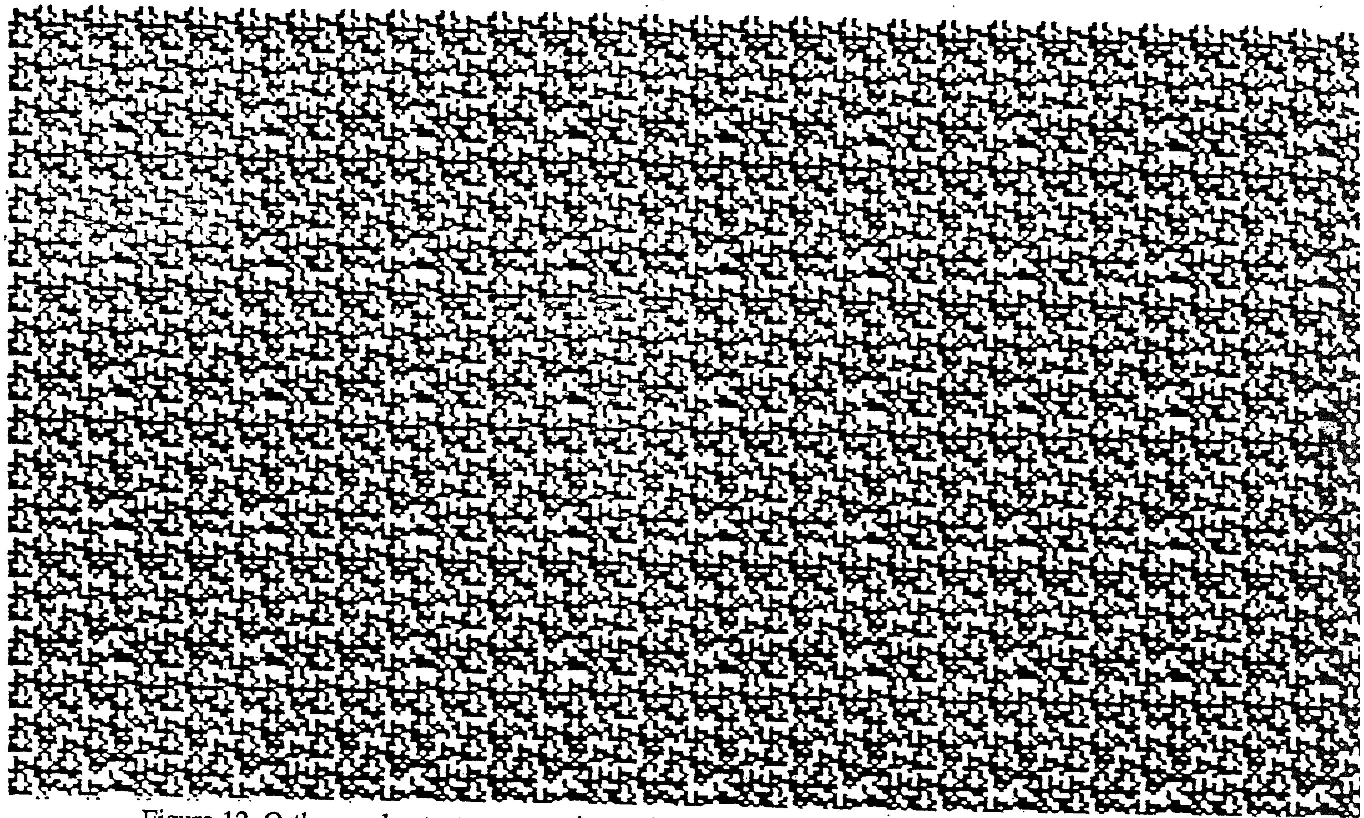


Figure 12. Orthogonal autostereogram image based on a unit random-dot square, with horizontal contour constraints. Overconvergence will result in perception of a flat plane, however.

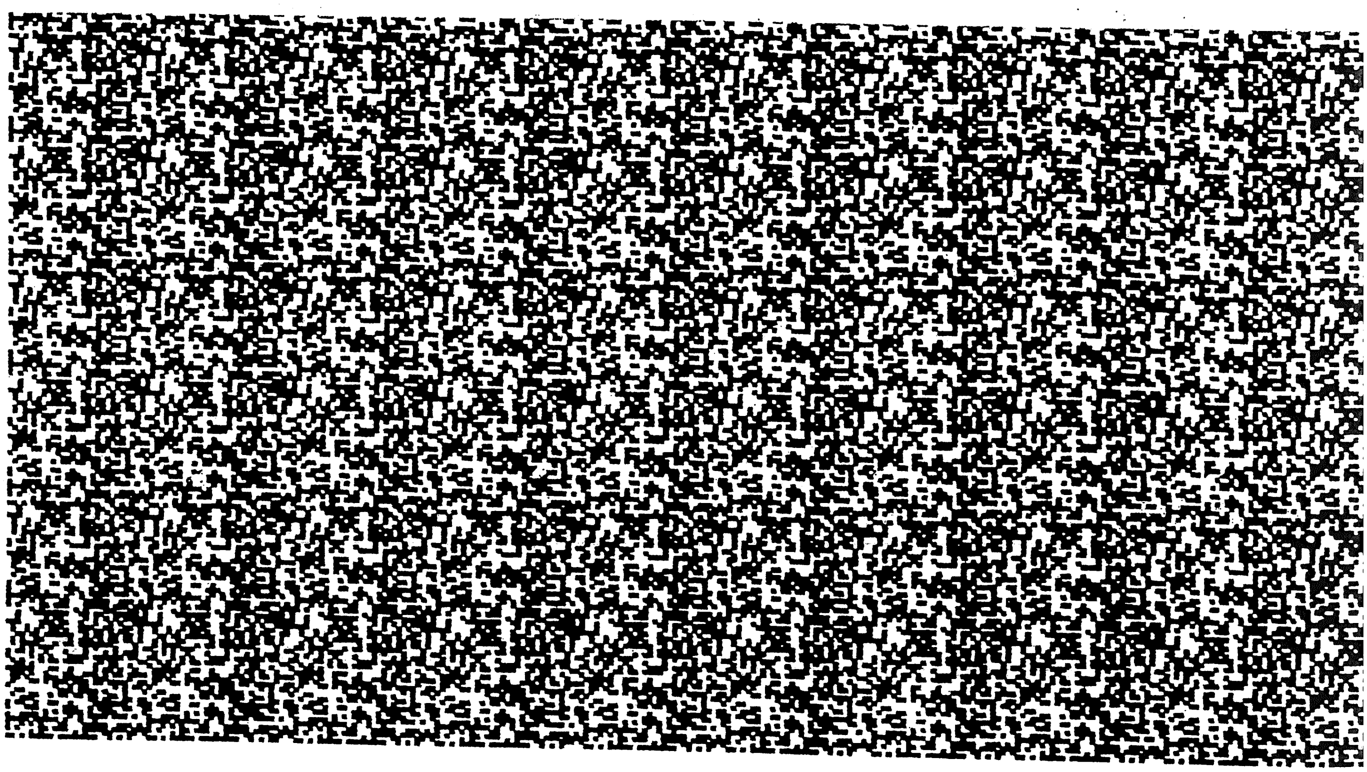


Figure 13. Orthogonal autostereogram image without image constraints in one orientation (this orientation). Image is constrained to vertical contours with respect to the orthogonal orientation.

stereoscopic patterns are possible. An example is given in Fig. 13, which can be viewed with the page in any one of the four cardinal orientations. Stork and Rocca (1989) also present an example of this type of autostereogram, based on independent development of the algorithm. Note that, since the algorithm is based on a repeating unit, these orthogonal stereograms also have the property of being able to form continuous wallpaper patterns indefinitely from copies of the original image.

Autolustergrams

The final type of cyclopean image to be presented is based on the percept of binocular luster rather than of stereopsis generated by binocular disparity. Binocular luster is produced by the presence of dissimilar detail in the two eyes, too fine to generate alternating interocular rivalry. An example of dissimilar detail is the presence of random dots uncorrelated between the two eyes in a given region of the visual field. In such situations, one has a kind of nebulous depth impression, which is definitely not a flat plane but is indeterminately localized in depth. A number of interesting characteristics of the perception of binocular luster have been previously described (Julesz and Tyler, 1976; Tyler and Julesz, 1976, 1980), including marked asymmetries between the appearance and disappearance of uncorrelated regions of dynamic random dots.

It is of course possible to produce binocular luster in the autostereogram paradigm merely by introducing regions of the fixation plane in which the dots are binocularly uncorrelated when convergence occurs. To our knowledge, binocular luster has not been previously used as a means of defining cyclopean forms, although it may occur as a byproduct of overlarge horizontal disparities or viewing a random-dot stereogram so that the disparities are vertical. One might assume that luster is a sufficiently vague percept that such forms would be rather ill-defined. Inspection of the autolustergrams in Figs. 14 and 15 shows that this is not the case. The narrow lines of luster only one element wide produce a razor-sharp impression of cracks in a pane of glass or diaphanous ribbons in space.

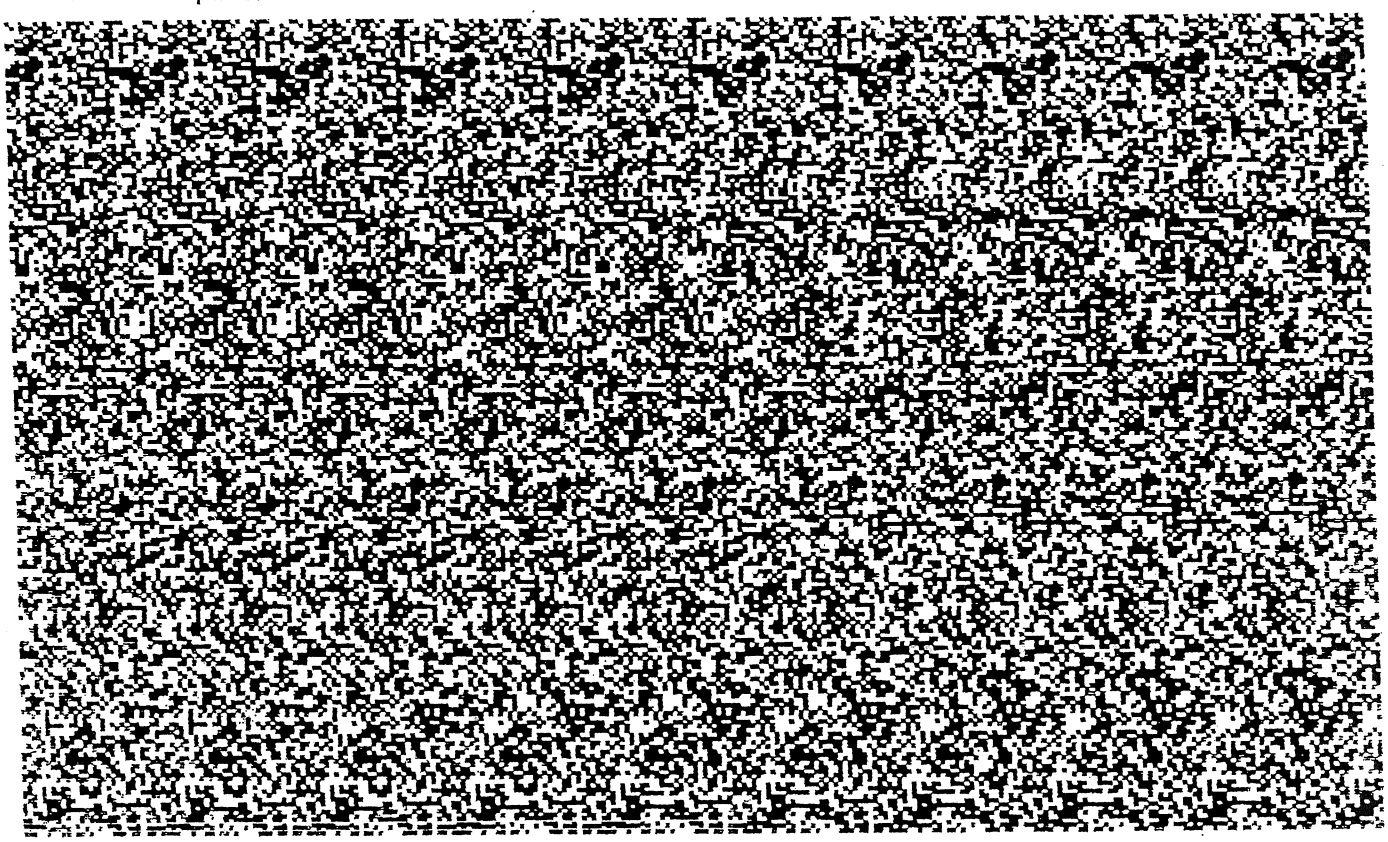


Figure 14. Autolustergram of curved lines in the form of a spider. Note the perceptual fineness of the lines, which are made from a single line of binocular complementation of the contrast.

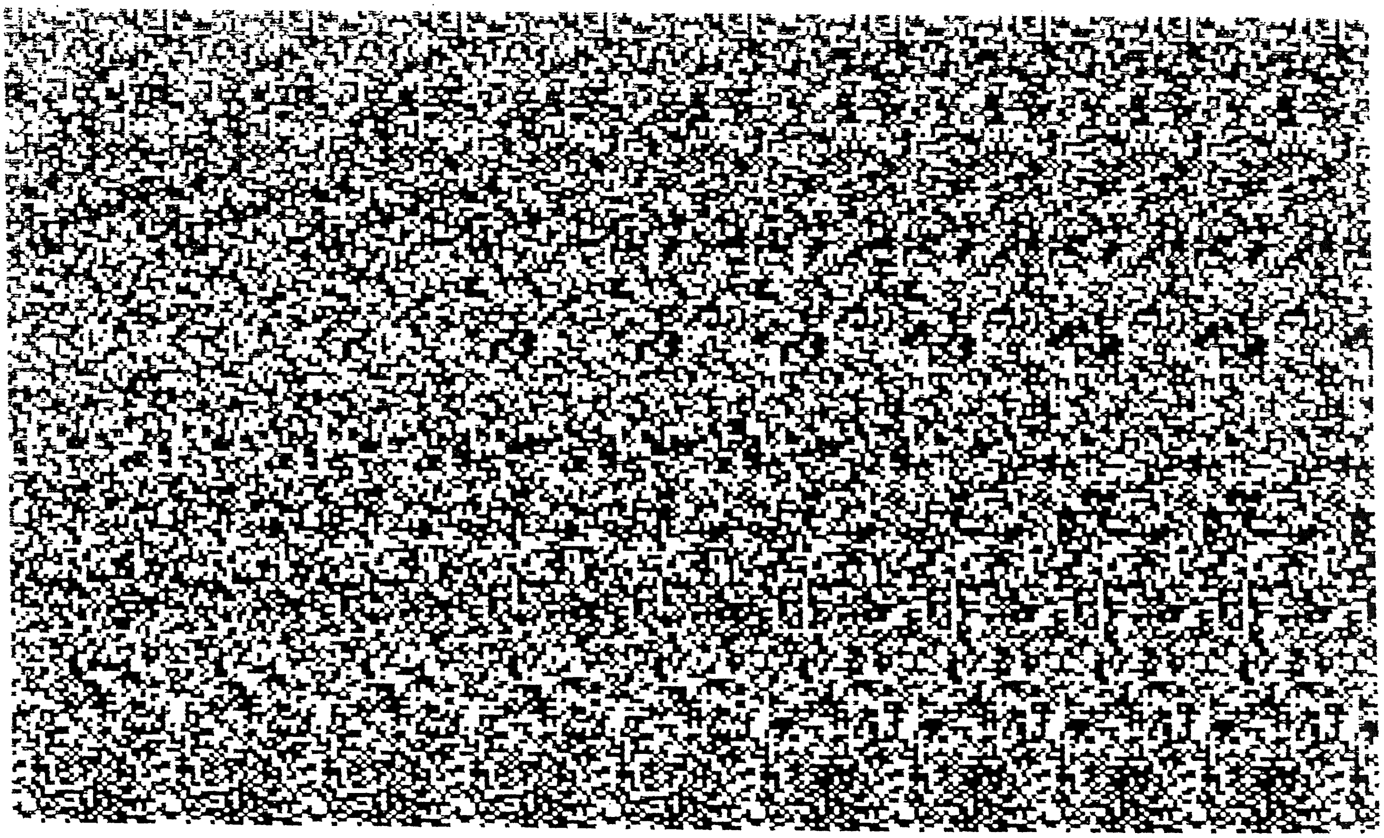


Figure 15. Autolustergram image in the form of a spider's web.

Conclusion

This paper describes a new stereographic technique that allows the reproduction of stereoscopic images in conventionally printed material, photocopies and decorative surfaces, without the need for any specialized viewing apparatus. For most observers stereopsis is relatively easy to obtain after a minimal amount of practice. The technique allows the generation of a large range of cyclopean images in a random dot format, although it is not suitable for classical stereograms containing monocular images with additional disparity cues. The technique would be readily adaptable for presentation dynamic stereoscopic images on conventional film or video equipment without a viewing apparatus. We hope that it will find many applications in the future.

More philosophically, one might wonder whether the autostereogram principle, which consists of using the overlap of repeating sequences in two underlying basis functions, generating an arbitrary secondary structure, might serve as a model for processes in other fields of science. For example, in molecular genetics there is currently a puzzle concerning the function of mysterious strips of DNA (introns) inserted into the main chromosomal sequence, but which do not have either the capacity to produce proteins or any other definite function. Some introns contain many repetitions of the same sequence of bases. Given that the cell contains a variety of mechanisms for duplicating genetic material, it seems an interesting possibility that intron duplicates might be matched up at some stage, not directly, but shifted by one repetition cycle. Small variations in the make-up of each cycle could then give rise to complex structures, just as they do in the autostereogram. Implausible as it may seem, such a mechanism can not be ruled out in the proliferating complexities of the world of molecular biology. Generalization of the autostereogram principle may also find application in such fields as cryptography and digital information processing.

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